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14. ABSTRACT

The Atchafalaya Bay system consists of a series of 5 shallow bays in southern Louisiana (U.S.A.) that are dominated by the circulation of the Atchafalaya River plume. Winter cold fronts have a significant impact on the resuspension and transport of sediments in this region and a better understanding of the circulation during these events is absolutely necessary for determining the sediment transport patterns of the Atchafalaya Bay system and the adjacent shelf area. Understanding the circulation of this region is also crucial for environmental studies as well. This work describes the implementation of the Navy Coastal Ocean Model . . .

15. SUBJECT TERMS

coastal processes, Atchafalaya Bay system, river plume, salinity front, sedimetn transport, remote sensing, NCOM, cold front

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Modeling the Circulation of the Atchafalaya Bay System during Winter Cold Front Events. Part 1: Model Description and Validation

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ABSTRACT

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The Atchafalaya Bay system consists of a series of five shallow bays in southern Louisiana (U.S.A.) that are dominated by the circulation of the Atchafalaya River plume. Winter cold fronts have a significant impact on the resuspension and transport of sediments in this region, and a better understanding of the circulation during these events is absolutely necessary for determining the sediment transport patterns of the Atchafalaya Bay system and the adjacent shelf area. Understanding the circulation of this region is also crucial for environmental studies as well. This work describes the implementation of the Navy Coastal Ocean Model (NCOM), a three-dimensional numerical circulation model for tide, river, and wind-forced circulation in the Atchafalaya Bay system. The model has a cell size (Δx) of ~800 m and is nested to a northern Gulf of Mexico model ($\Delta x \sim 5000$ m), which is itself nested to the global NCOM ($\Delta x = 1/8°$). Atmospheric forcing is supplied by the Navy Operational Global Atmospheric Prediction System (NOGAPS) ($\Delta x = 1°$). These models are used to simulate the hydrodynamics of the Atchafalaya Bay system and Atchafalaya river plume between December 1997 and January 1998 during the passage of three winter cold fronts. The water levels, salinity, and currents predicted by NCOM are in reasonable agreement with available measurements and tide-gauge elevation data. Errors in ebb tides and wind-driven circulation are attributable to uncertainties in the bathymetry and the low spatial and temporal resolution of the NOGAPS wind fields.

ADDITIONAL INDEX WORDS: *Coastal processes, Atchafalaya Bay system, river plume, salinity front, sediment transport, remote sensing, NCOM model, cold front.*

INTRODUCTION

This paper describes and validates a realistic numerical hydrodynamic simulation of the Atchafalaya Bay region, which is an important component of Louisiana's coastal ecosystem. The shallow, muddy, and nutrient-rich environments of coastal Louisiana contribute substantially to the seafood and recreational economies of the state, but these sensitive areas are threatened by rising sea level and coastal erosion, with short-term rates of shoreline retreat as high as 10 m/y (PENLAND *et al.,* 2005). The extensive coastal wetlands also play an important role as buffers to protect the city of New Orleans from storm surges during hurricanes. Ultimately, the long-term survival of this fragile environment is dependent on water circulation and sediment transport. A better understanding of hydrodynamic and sediment transport processes within these coastal areas is, therefore, essential from economic, environmental, and societal perspectives.

Numerical models for circulation and sediment transport have the potential to provide accurate forecasts over large coastal regions, thus providing an important and cost-effective tool for coastal management. Perhaps more important, these models can also provide long-term hindcasts, enabling coastal scientists to determine how a particular region has been affected in the past by changes in river discharge, sediment transport, and energetic events such as winter cold fronts (or tropical storms) over a period of several years. To apply these models to river-dominated bays and estuaries, it is imperative that they first be validated with *in situ* field data as well as remotely sensed observations (*i.e.,* data obtained from satellites and flyovers).

Background and Study Area

The 1500 km² Atchafalaya Bay system (Figure 1), which comprises five contiguous bays: Vermilion Bay, West and East Cote Blanche Bays, Atchafalaya Bay, and Fourleague Bay, represents one of Louisiana's most dynamic coastal environments. This region was an abandoned delta complex of the Mississippi River until the 1950s when a new episode of delta building began (ROBERTS, ADAMS, and CUNNINGHAM, 1980; SCHLEMON, 1975). Since the 1970s, the Atchafalaya and Wax Lake subaerial deltas have grown where Atchafalaya River water is discharged into Atchafalaya Bay via the

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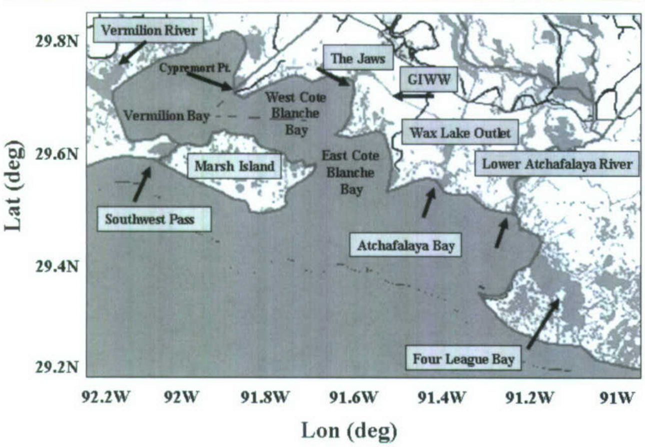

Figure 1. Regional map showing Atchafalaya Bay system and locations referred to in the text. GIWW = Gulf Intracoastal Waterway.

main river channel and Wax Lake Outlet (ALLISON *et al.,* 2000; ROBERTS, ADAMS, and CUNNINGHAM, 1980). Because of the high sediment load carried by this water, the coastline of the Chenier Plain to the west of Atchafalaya Bay is advancing at rates as high as 50 m/yr (HUH, WALKER, and MOELLER, 2001) instead of eroding, which is the dominant trend of coastal Louisiana. Between 1987 and 2001 the coastline of the eastern chenier plain (92.4°W) accreted as much as 600 m of mud, advancing at an average rate of 28.9 m/yr (DRAUT *et al.,* 2005). In addition, as indicated by recent studies (DRAUT *et al.,* 2005; HUH, WALKER, and MOELLER, 2001; KINEKE *et al.,* 2006), energetic resuspension events associated with winter cold fronts and tropical storms play a important role in enhancing the accretion of mud along the coastline of the Chenier Plain as well.

The outflow from the Mississippi River into the upper Atchafalaya basin is regulated at 15% to 29% of the total Mississippi River inflow (ALLISON *et al.,* 2000), but the Atchafalaya River carries 40% to 50% of the total Mississippi sediment load (MOSSA and ROBERTS, 1990). The lower Atchafalaya River (LAR) transports about 70% of the upper Atchafalaya River freshwater discharge and is, therefore, a significant source of both freshwater and sediment for the entire bay system. The LAR's maximum freshwater discharge occurs from January through July, with transport rates as high as 7200 m^3/s (U.S. GEOLOGICAL SURVEY, 2001). The Wax Lake Outlet (WLO) transports most of the remaining 30% (ALLISON *et al.,* 2000) of the upper Atchafalaya freshwater discharge. The freshwater outflow from the WLO can be as high as 5800 m^3/s from January through July (U.S. GEOLOGICAL SURVEY, 2001).

Between October and April, 20 to 30 cold fronts pass through this region, with intervals of 4 to 7 days, and their strong and variable winds affect the circulation throughout the bay (KAHN and ROBERTS, 1982; KINEKE *et al.,* 2006; MOELLER *et al.,* 1993; WALKER and HAMMACK, 2000, hereinafter WH00). WH00 showed that bay water levels west of Atchafalaya Bay fall ~1 m on average because of the strong northwesterly to northerly winds associated with the passage of cold fronts. The winds generated by cold fronts also influence the direction of the LAR and WLO outflow plumes on the adjacent continental shelf, altering the transport and deposition of sediments in the region (KINEKE *et al.,* 2006; WH00). However, satellite observations indicate that the sediment plumes result from both resuspension by strong postfrontal winds as well as flushing of the bay. It is estimated (WH00) that 10^7 metric tons of sediment (12% of the total sediments delivered to the coast annually by the Atchafalaya River) are transported from the bays to the continental shelf annually by winter storms. Sediment transport to the shelf may be better quantified with additional data or models because this preliminary estimate was based on extrapolation of time series measurements from only one station within the entire bay system.

Objective

Previous studies have used satellite observations and field measurements to examine various aspects of resuspension, sediment transport, and sedimentation in the region but have not attempted to model the dynamics of these processes in detail (MOELLER *et al.,* 1993; PEREZ *et al.,* 2000; WH00). The objective of this work is to describe a numerical model of circulation within the bay system and validate the results with available observations during cold fronts, specifically during the period studied by WH00. The validated circulation model will be used in future sediment transport studies of the region. The influence of combined tides and atmospheric forcing on plume dynamics and exchange processes with the continental shelf are discussed in a companion paper (COBB, KEEN, and WALKER, 2008).

METHODS

The Navy Coastal Ocean Model (NCOM)

The Navy Coastal Ocean Model is a three-dimensional, primitive equation, hydrodynamic model that employs the hydrostatic, incompressible, and Boussinesq approximations to solve the conservation equations for the current velocity, temperature, and salinity as well as the continuity equation (MOREY *et al.,* 2003). It uses Smagorinsky horizontal mixing coefficients and the Mellor–Yamada level 2.5 parameterization for vertical mixing. The model equations are solved on an Arakawa C grid. The horizontal grid is curvilinear and uses a hybrid vertical coordinate system, which consists of both fixed z levels in deep water and variable σ coordinates in shallow water. The free surface and vertical mixing equations are solved implicitly; the other terms are treated explicitly. NCOM can be nested to a coarse-grid model to supply boundary conditions at the open boundary of the domain. NCOM has been validated at global (BARRON *et al.,* 2004; KARA *et al.,* 2006) and basin scales (KO, PRELLER, and MARTIN, 2003). It also compares well with observations from coastal regions (*e.g.,* KEEN *et al.,* 2006; MOREY *et al.,* 2003).

The surface boundary condition for all of the simulations discussed herein consists of wind speed and direction at 6-hour intervals interpolated from the 1° Navy Global Operational Atmospheric Prediction System (NOGAPS) forecast

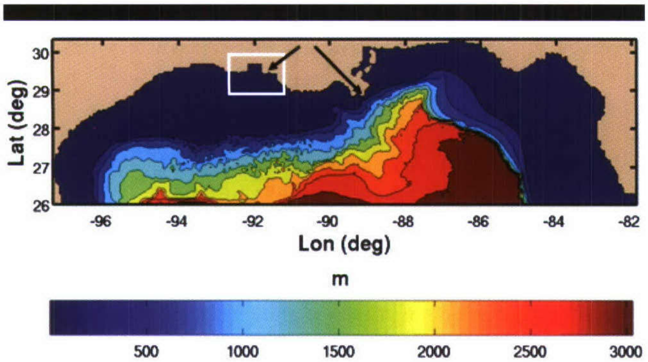

Figure 2. Northern Gulf of Mexico (NGOM) grid bathymetry. The contour spacing is approximately 300 m. The arrows indicate the locations of the Atchafalaya and Mississippi River inflows. The white box indicates the location of the nested Atchafalaya Bay grid.

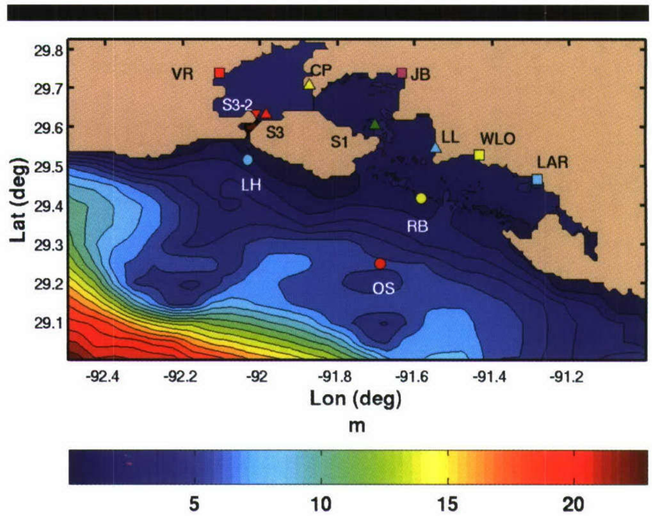

Figure 3. Bathymetry, inflow points, and data locations of the Atchafalaya Bay system. Contour spacing is 2 m. The squares indicate sources of freshwater: LAR = lower Atchafalaya River; WLO = Wax Lake outlet; JB = Jaws Bay; VR = Vermilion River. Circles indicate IHO tidal stations: RB = Rabbit Island Pass; LH = Lighthouse Point; OS = offshore point. Data location points from Walker and Hammack (2000) are indicated by triangles: S1 = Site 1; S3 = Site 3; S3-2 = alternate Site 3, down triangle; CP = Cypremort Point; LL = Luke's Landing. Wind measurements were also collected at Cypremort Point.

fields. Open boundary conditions for NCOM comprise water levels and vertically integrated transports, which can consist of separate subtidal and tidal flows, and profiles of temperature, salinity, and currents. A radiation boundary condition is used for momentum, heat, and mass along the open boundary. River inflow is represented by a boundary condition for transport, temperature, and salinity at specified grid cells. Specific boundary conditions for the simulations discussed in this paper are discussed in the following sections.

Model Simulations

Model simulations were completed using NCOM for July 1997 to January 1998, which includes the measurement period described by WH00. NCOM is run on two domains in this study: (1) a Northern Gulf of Mexico grid (Figure 2) with a resolution of ~5 km; and (2) a smaller nested grid (Figure 3) with a cell size of ~800 m.

The Northern Gulf of Mexico Simulations

Two kinds of simulation have been run on the Northern Gulf of Mexico (NGOM) domain: (1) tides only; and (2) realistic forcing with winds, tides, and river inflow. The grid has a vertical discretization of 20 z levels and 4 σ levels with a minimum depth of 1 m. A time step of 500 seconds is used. This grid is too coarse to resolve either Vermilion Bay or West and East Cote Blanche bays, so an artificial bay region was added to the original NGOM grid to have a general representation of the inner bays. The NGOM grid extends from 97.48° W to 81.53° W and 26.0° N to 30.40° N with 320 and 89 cells along the easting and northing axes, respectively. The NGOM initial and boundary conditions for temperature and salinity were obtained from the 1/8° global NCOM implementation. The NGOM simulations are designed to supply boundary conditions to the Atchafalaya Bay nested model described in the following section. Tidal forcing at the open boundary of the NGOM grid consists of water levels and vertically integrated transports for eight constituents: K1, O1, P1, Q1, K2, M2, N2, S2. The tidal factors (phase and amplitude) are found from the global tide model of Egbert and Erofeeva (2002). The tide-only NGOM simulation was run for December 15, 1997, to January 15, 1998, for the purpose of tidal validation.

The NGOM simulations include four inflow locations (Table 1): the LAR, the WLO, and two major outflows from the Mississippi River (Mississippi-A and -B) (their approximate locations are indicated by arrows in Figure 2). The discharges for the Mississippi-A and -B are monthly climatologies (Barron and Smedstad, 2002); note that the term "climatology" indicates that the river discharge was determined from historical records of discharge and is only a monthly mean value in this case. The LAR and WLO discharges were compiled from USGS data (U.S. Geological Survey, 2001) and Walker and Hammack (1999). USGS discharge data were unavailable for November to December 1997 for the LAR and for January 1998 for the WLO. The missing data were estimated by combining the USGS measurements and the Walker and Hammack (1999) observations. Consequently, approximately 60% of the upper Atchafalaya River discharge goes to the LAR in this study. This is similar to the estimated average of 70% typically stated in the literature, which is

Table 1. *Mean monthly river discharge conditions for the northern Gulf of Mexico model domain. Note that the Mississippi A and B salinities were held at 10 psu, and their temperatures are listed in parentheses in the Miss. A discharge column.*

Month and Year	Temp. (°C)	Salinity (psu)	Discharge (m^3/s)			
			Atchafalaya	WLO	Miss. A	Miss. B
November 1997	12	5	1849	1260	3825 (12)	3825
December 1997	8	2	2291	1564	5527 (8)	5527
January 1998	10	0	5323	3814	6956 (14)	6956

Table 2. *Mean monthly river discharges for the Atchafalaya Bay system model domain.*

	July 1997 m^3/s	August 1997 m^3/s	September 1997 m^3/s	October 1997 m^3/s	November 1997 m^3/s	December 1997 m^3/s	January 1998 m^3/s
Lower Atchafalaya River	3017	1843	1555	1465	1849	2291	5323
Wax Lake	2082.4	1185.6	1065.2	1238	1260	1564	3814
Jaws Bay	173	100	100	120	150	150	186
Vermilion River	28.2	24.6	27.9	23.8	19.6	24.1	18.3
Cypremort Point	43	43	43	43	43	43	43

based on long-term measurements (*e.g.,* VAN HEERDEN, WELLS, and ROBERTS, 1983). The mean monthly temperature and salinity values for the LAR and WLO (Table 1) were obtained by using the minimum values of the data taken at Site 1 (91.70° W, 29.60° N) (see Figure 3 for location) by WALKER and HAMMACK (1999) in November 1997 through January 1998. The temperatures of the Mississippi-A and -B rivers were estimated using available data for the time (WALKER and HAMMACK, 1999) and their salinity values were set to 10 psu.

The Atchafalaya Bay Simulations

The Atchafalaya Bay grid (ABG) (Figure 3) uses bathymetry data from NOAA (NOAA, 2005), which covers most of the Atchafalaya Bay system at a resolution of approximately 90 m; however, it excludes Vermilion Bay and the adjacent continental shelf. The NOAA bathymetry extends from the shore to approximately the location of point RB in Figure 3, spanning the entrance to Atchafalaya Bay. Consequently, a uniform depth of 2.5 m is set for Vermilion Bay, and offshore depths are interpolated from the NGOM grid. In addition, a channel representing Southwest Pass (Figure 1) was created to allow water exchange between Vermilion Bay and the continental shelf. The channel depth of 24 m is based on previous measurements (WH00). The bathymetry used for the ABG is subsampled from the actual bathymetry to a resolution of approximately 800 m. The coastline and island boundaries used in the domain were determined for the entire region (Figure 3) using the World Vector Shoreline database from the National Geospatial-Intelligence Agency (NGA). The ABG grid extends from 92.5° W to 91.0° W and 29.0° N to 29.99° N with 188 and 125 cells along the easting and northing axes, respectively. All of the Atchafalaya simulations in this study use four z levels and four terrain-following σ levels. The σ levels are applied when the depth is less than 15 m. A minimum depth of 1 m is used. A time step of 92.9 seconds is used for realistic simulations and 300.0 seconds for tide-only simulations.

It is important to have realistic initial conditions for NCOM within the entire bay system prior to the validation period (December 23, 1997, to January 12, 1998). Thus, the ABG model is run from July 2 to November 8, 1997, to allow the development of the estuarine circulation and the river plumes. The final state of this simulation (water levels, currents, temperature, and salinity) is used to restart the model for the validation period. The spin-up run includes the same tidal boundary conditions and atmospheric forcing as the NGOM simulation, but no subtidal forcing (*i.e.,* NGOM baroclinic boundary conditions) is imposed at the open boundary. The initial and offshore boundary condition values for the temperature and the salinity are specified to be 20°C and 35 psu, respectively. Note that because of these initial conditions and the lack of any freshwater sources specified for Four League Bay (see Figure 1), a small patch of high salinity is trapped at the end of this bay. This high salinity water is mixing with the river plume water but at a very slow rate.

The ABG open boundary conditions during the study period (November 8, 1997, to January 11, 1998) are interpolated from the NGOM 3-hour output fields of water level, temperature, salinity, and currents. Tidal forcing is not applied at the ABG boundary because the tides are already incorporated into the open boundary condition obtained from the NGOM simulation. The NOGAPS wind velocity fields used for the ABG simulations are interpolated from the same wind fields used to drive the NGOM simulation.

The primary sources of freshwater for the ABG simulation are the LAR and WLO, but to achieve realistic salinity values within Vermilion Bay, West Cote Blanche Bay, and East Cote Blanche Bay, we require additional sources of freshwater. Although there are numerous freshwater outlets into the Atchafalaya Bay system (GOREE *et al.,* 2001; SWARZENSKI, 2003), only those having significant discharge are included. For example, the Jaws Bay and Cypremort Point Gulf Intracoastal Waterway (GIWW) outlets (see Figure 3 for locations) play an important role in determining the salinity levels of the western bays. The Vermilion River (see Figure 3 for location) is also included because of its close proximity to a location at which salinity was measured by WH00. Monthly mean discharges at the LAR and WLO (Table 2) for July through October 1997 are from the USGS database. The minimum monthly temperatures measured at Site 1 are used for the LAR and WLO for the entire simulation period (Table 3). The LAR and WLO inflow salinities (Table 4) were adjusted to improve the model-observation agreement but are maintained between the minimum and mean monthly values of the Site 1 salinity measurements. The discharges for November 1997 through January 1998 at the LAR and WLO outlets were estimated in the same way as for the NGOM simulation.

There are several minor but locally important sources of freshwater for the Atchafalaya Bay system in addition to the LAR and WLO. The monthly mean discharges for January to July at Jaws Bay (Table 2) are estimated using 1997 data from SWARZENSKI (2003). The Jaws Bay August-to-December discharges, which are not available, are estimated using the WLO discharge for July–August. The ratio of the WLO August and July discharge values is 0.57. Applying this ratio to

Table 3. *Mean monthly river discharge temperature for the Atchafalaya Bay system model domain.*

	July 1997 (°C)	August 1997 (°C)	September 1997 (°C)	October 1997 (°C)	November 1997 (°C)	December 1997 (°C)	January 1998 (°C)
Lower Atchafalaya River	29	28	25	16	12	8	10
Wax Lake	29	28	25	16	12	8	10
Jaws Bay	30.8	31	28.8	21.2	15.8	12.4	13.4
Vermilion River	29	29	25	16	10	8	10
Cypremort Point	29	29	25	16	10	8	10

the July data for the WLO results in a mean August discharge of approximately 100 m^3/s into Jaws Bay (assuming the WLO and Jaws Bay outlet have similar trends). Between August and December, we gradually increase the Jaws Bay discharge rate to the January value, following the general trend of the WLO. The mean monthly temperature (Table 3) and salinity (Table 4) values measured at Site 1 are used for Jaws Bay (JB) but with two exceptions: (1) the maximum salinity measured at Site 1 is used for November, and (2) the salinity in December is increased above the mean to improve the model's accuracy. The Vermilion River discharges (Table 2) are obtained from mean monthly values measured at Perry, Louisiana, and the constant discharge value used for Cypremort Point is estimated using measurements taken between July 1997 and September 2000 (Goree *et al.,* 2001). The temperature and salinity values of both the Vermilion River and Cypremort Point (Tables 3 and 4) are specified using the minimum values measured at Site 3 (91.98° W, 29.63° N) (see Figure 3 for location) by Walker and Hammack (1999).

COMPARISON OF MODEL PREDICTIONS AND OBSERVATIONS

Wind Vectors

Winter cold fronts of varying intensity pass over the Atchafalaya bay region between October and April. As a cold front passes, the wind direction rotates clockwise, changing from a prefrontal southerly wind (blowing to the north) to postfrontal northerly wind (Moeller *et al.,* 1993). Three cold fronts passed over the Atchafalaya bay region between December 23, 1997, and January 12, 1998. The physical responses of the western bays (East Cote Blanche, West Cote Blanche, and Vermilion Bays) to these three cold fronts are reviewed in detail by WH00. We have used the WH00 wind speed and direction data collected every 30 minutes at Cypremort Point during this period. The first two cold fronts were part of the same storm system and occurred between December 26 and 30. The third cold front occurred between January 7 and 9.

The NOGAPS wind vectors at Cypremort Point (CP) (Figure 4A) reveal maximum prefrontal southerly winds of 8.6 m/s on December 24, followed by northerly winds. The maximum measured wind (Figure 4B) is noticeably stronger than the model during this period, however. The measured wind velocity was interpolated to the same dates as the NOGAPS output in Figure 4B for the purpose of comparison. The wind returned to southerly prior to the second cold front on December 29. The first week of 1998 was dominated by a southerly wind until January 7, when a third cold front occurred. The NOGAPS wind captures these changes in wind direction well, but the magnitude is overpredicted for the southerly wind between the second and third cold fronts and underpredicted during periods of strong northerly winds. The NOGAPS wind should therefore provide adequate forcing for both the NGOM and ABG models during the passage of each cold front, when the wind direction is changing rapidly, but the strong postfrontal winds will be underpredicted. In addition, the model's response to the steady southerly winds between the second and third cold fronts may be too strong.

Tidal Elevations

A purely tidal NGOM-ABG nested simulation was run for the period of December 15, 1997, to January 15, 1998. The model-predicted tidal elevations are compared with elevations extracted from the IHO (International Hydrographic Office) database for two tidal stations within the Atchafalaya Bay system (Figure 5): Light House Point (LH in Figure 3); and Rabbit Island Pass (RB). The means of both the model and the IHO data time series have been removed to eliminate any subtidal biases and differences in reference elevation. The model skill is quantified using a correlation coefficient (Bendat and Piersol, 2000).

The correlation coefficients R for elevations at LH and RB are 0.94 and 0.91, respectively. The phase of the predicted

Table 4. *Mean monthly river discharge salinity for the Atchafalaya Bay system model domain.*

	July 1997 (psu)	August 1997 (psu)	September 1997 (psu)	October 1997 (psu)	November 1997 (psu)	December 1997 (psu)	January 1998 (psu)
Lower Atchafalaya River	0	2	2	4	5	4	3
Wax Lake	0	2	3	4	5	4	3
Jaws Bay	4.4	4.3	5.2	8	9	9	3.5
Vermilion River	1	3	2	6	7	3	0
Cypremort Point	1	3	2	6	7	3	0

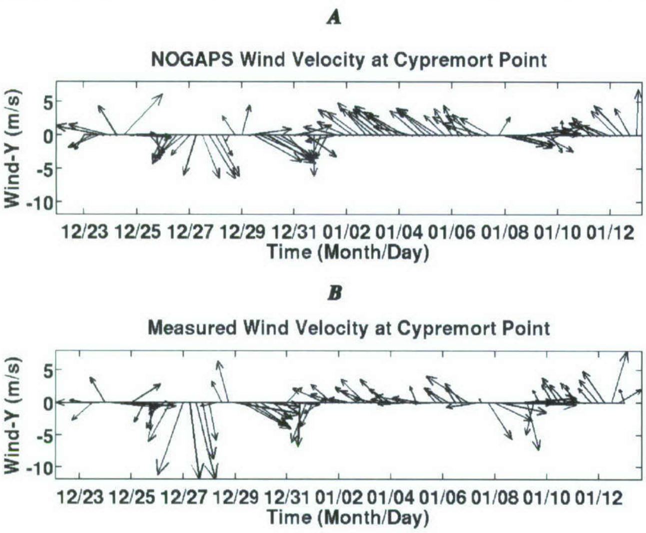

Figure 4. Wind vectors at Cypremort Point between December 23, 1997, and January 13, 1998. (A) Interpolated NOGAPS forecast. (B) Measured wind from Walker and Hammack (2000).

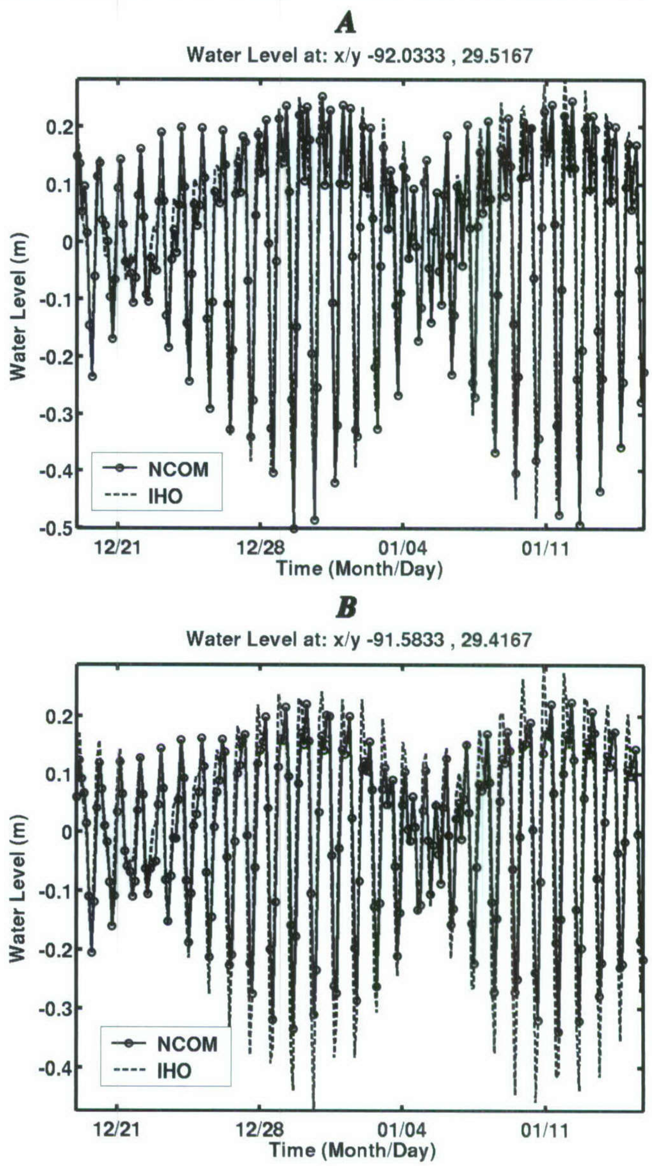

Figure 5. NCOM (solid line with circles) and IHO (dashed line) tide forced sea surface elevation model-data comparison from December 19, 1997, to January 15, 1998, at (A) Light House Point (92.0333° W, 29.5167° N) and (B) Rabbit Island Pass (91.5833° W, 29.4167° N).

and measured elevations agrees at both stations whereas the amplitude is best at LH. The predicted tidal amplitude at RB is less than the IHO data, especially during low tides. The disagreement at Rabbit Island Pass is not surprising because the shallower (*i.e.,* inner bay) regions of the ABG domain were created using bathymetry data collected in 1934. Since this time there have been substantial changes in the bathymetry of Atchafalaya Bay and East Cote Blanche Bay (WALKER *et al.,* 1997). In particular a number of oyster reefs were removed from the vicinity of RB after 1934 (STONE, ZHANG, and SHEREMET, 2005). We also compare the IHO predictions at RB with the modeled sea surface elevation at a point further offshore from RB (location OS in Figure 3). The *R* value at OS is 0.99, indicating that the model's prediction of the tidal amplitude is significantly better where the model bathymetry is based on more recent observations.

Combined Water Levels

To validate the realistic ABG's sea surface elevation, we use hourly water level data measured at Luke's Landing (LL in Figure 3) by the U.S. Army Corps of Engineers (New Orleans District) during the same period as the WH00 current and salinity measurements. The water level predicted by the ABG model at Luke's Landing is plotted with the observations in Figure 6. The model results reveal the same trend as the observations, but there are several discrepancies. First, the model underpredicts the low water levels at Luke's Landing; this is probably because of differences between the model and the actual bathymetry as previously discussed. The model also fails to reproduce the large fluctuations in the elevation during both high and low tides. This could be due to local bathymetric effects caused by the location of the tide gauge as well as the differences between the NOGAPS and the measured winds. An example of this occurs in the measured water levels on December 27. During this time, strong postfrontal northerly winds created a maximum setdown in the observed water level that was approximately 0.3 m larger (*i.e.,* more negative) than the water level predicted by the model. The measured winds were significantly stronger than the NOGAPS winds during this period (Figure 4).

During each cold front event, there is a flushing of the western bays (East Cote Blanch Bay to Vermilion Bay) by the strong postfrontal northerly winds (WH00), which results in a significant setdown in the water levels at LL (Figure 6). The westerly and northerly winds of the cold fronts also redirect the river plume's westward transport to the east for

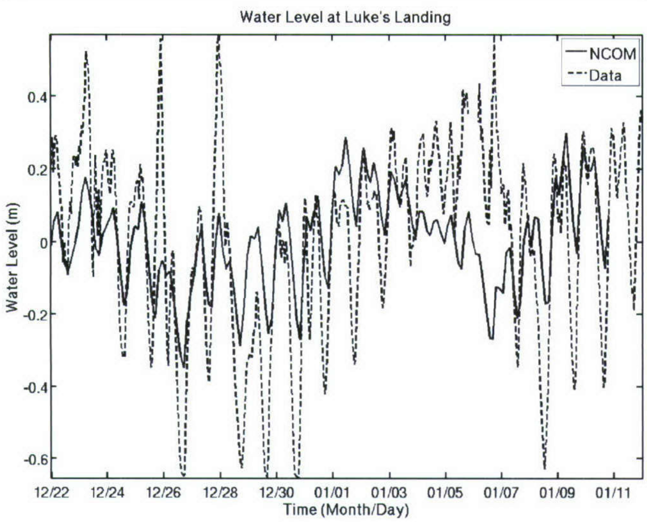

Figure 6. Water level (m) at Luke's Landing (LL in Figure 3). The solid line represents the wind-tide-river forced ABG simulation. The dashed line represents the water level time series data reproduced from Walker and Hammack (2000). The means have been removed from both time series.

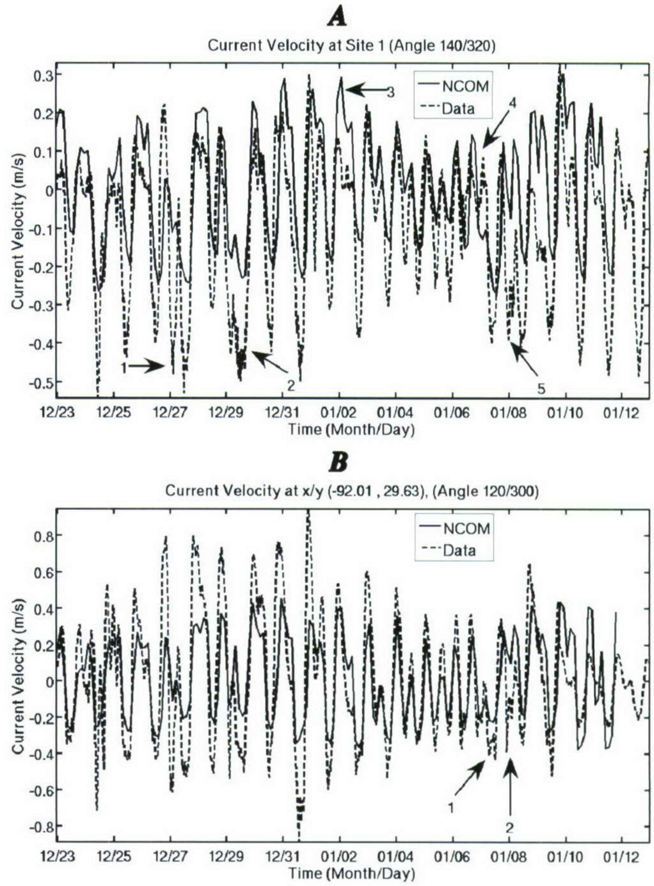

Figure 7. NCOM ABG simulation (solid line) and measured (dashed line) surface current magnitude (m/s) between December 23, 1997, and January 13, 1998: (A) Site 1. The current velocities have been projected along an axis with a direction of 140°/320°; (B) Site 3. The model results are from the western side of Southwest Pass (site S3-2 in Figure 3). The observed current velocities have been projected along an axis with a direction of 30°/210° and the model has been projected along 120°/300°. See text for explanation. Arrows indicate important differences between the model and the data.

several days, typically. Following the second cold front event of December 29, the observed southerly wind was light and variable (Figure 4). Stronger and less variable southeasterly winds were determined from NOGAPS; nevertheless the normal westward transport of the river plume was not reestablished until around January 5. During the intervening period (January 1–5), the water levels at LL increased as the southerly winds forced river plume water into the western bays. The shelf water does not enter the bay system in the vicinity of LL during this period because of the outflow of the river plume. As the westward transport of the model's river plume reestablishes itself, the water level of the model at LL starts decreasing and diverging from the measured water level (Figure 6). This premature decrease in the water level of the model at LL suggests that the strong and steady southerly NOGAPS winds reestablish the westward flow of the model's river plume earlier than the actual river plume.

Current Vectors

The measured current velocities at Sites 1 and 3 (Figure 7) are projected along axes that are aligned with the tidal flow (WH00). Primary current axes orientations of 140°/320° (flood/ebb flow direction measured counterclockwise from east) and 30°/210° were used at Sites 1 and 3, respectively. The currents from the model at Site 1 are projected along these same axes. By convention, currents entering the bays are positive. The model grid does not accurately reflect the coastline and bathymetry at Site 3. Therefore, the predicted currents at a location (92.01° W, 29.63° N; S3-2 in Figure 3) that is slightly closer to the entrance of Southwest Pass are compared to the observations at Site 3. We use a current axis of 120°/300° instead of 30°/210° to determine incoming and outgoing currents in the same manner as WH00. We do not expect perfect agreement between the measured and modeled currents at Southwest Pass because the model bathymetry of Vermilion Bay is only approximate and the pass was artificially created. Nevertheless, the model results at this point will demonstrate that the magnitude and phase of the predicted currents at Southwest Pass are comparable with the observations at Site 3.

The model-predicted incoming (positive) current velocities at Site 1 (Figure 7A) are in good agreement with the observations for most of the study period. The overprediction of the incoming currents on January 2 (indicated by arrow 3 in Figure 7A) is consistent with the disagreement for the water levels at Luke's Landing (Figure 6); the predicted water level increases too rapidly because the modeled incoming currents are too strong. During the period of steady southerly winds between the second and third cold fronts, the flood currents from the model and the observations are in good agreement, even though the NOGAPS wind is stronger than the measured winds.

The outgoing (negative) modeled currents at Site 1 are consistently underpredicted. The model-observation comparison of the tidal elevation at RB (Figure 5B) suggests that this is partly due to the bathymetry, but, as discussed above, the atmospheric forcing also contributes to the error. In particular, the measured outgoing currents during the postfrontal phase of the first (December 27) and second (December 29) cold fronts are underpredicted (indicated by arrows 1 and 2) by the model because the NOGAPS winds are weaker than the measured winds (Figure 4). The prefrontal winds of the third cold front (January 7) generate outgoing currents in the model, but the observations indicate a more tidal pattern to the currents; see arrow 4 in Figure 7A. The measured currents also indicate a more prolonged period of outflow following the third cold front, resulting in a significant error during the January 7 to January 8 period; see arrow 5 in Figure 7A. These discrepancies are consistent with differences between the NOGAPS and the measured wind during this period (Figure 4). After January 9 the model's skill improves significantly as does the agreement between the NOGAPS and the measured winds.

The flow through Southwest Pass is dominantly tidal during spring tides. The predicted flow at S3-2 (Figure 7B) is generally in phase with the observations except around January 8 (indicated by arrow 2), but the magnitudes are underpredicted during the first and second cold fronts. The agreement is quite good during the passage of the third cold front around January 7 (see arrow 1), unlike Site 1 (arrow 4 in Figure 7A). This suggests that the flow through Southwest Pass, as opposed to West Cote Blanche Bay, dominates the circulation at Site 3 during this period. Between January 7 and 8 (arrow 2 in Figure 7B) the measurements indicate a large outgoing current that is not reproduced by the model at S3-2. This discrepancy is most likely due to differences between the NOGAPS and the measured postfrontal winds around this time (Figure 4). The large outgoing currents measured at Site 3 at this time are consistent with the Site 1 (arrow 5 in Figure 7A) and the Luke's Landing observations (Figure 6) as well. Following the third cold front there is good agreement between the model and the observations.

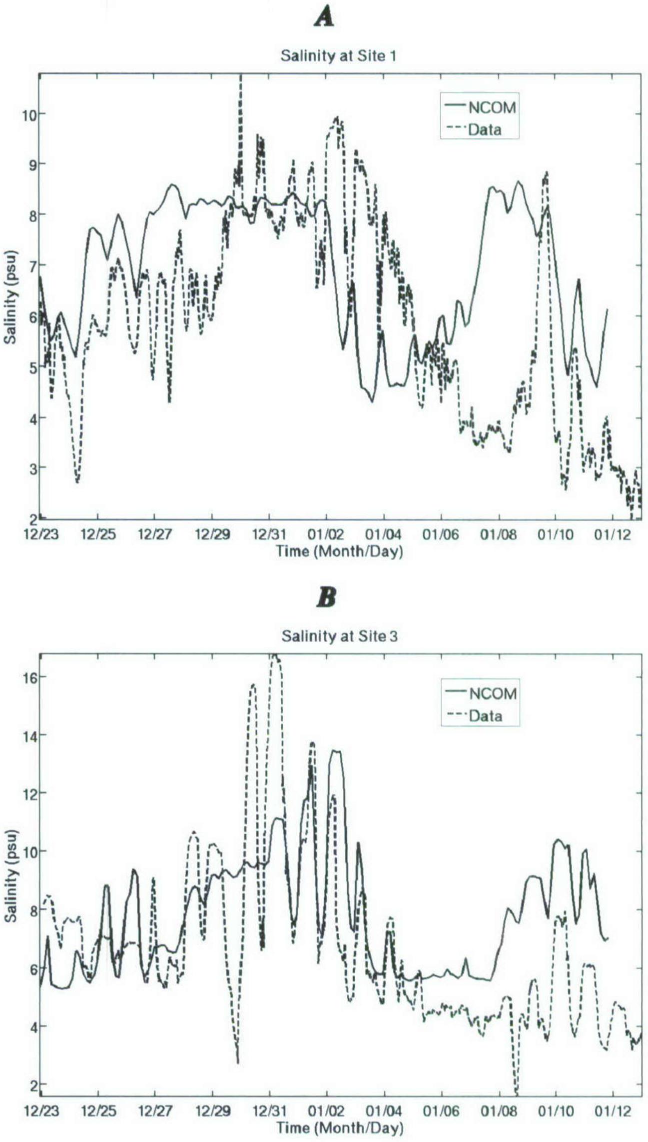

Figure 8. NCOM (solid line) and measured (dashed line) salinity (psu) between December 23, 1997, and January 13, 1998: (A) Site 1; (B) Site 3.

Salinity

To validate the predicted salinity of the model, we use the WH00 measurements at Sites 1 and 3. The trends of the model-predicted and measured salinity time series at Site 1 (Figure 8A) are in good agreement for most of the validation period. The salinity is overpredicted following the passage of cold fronts on December 25–30 and January 7–9. These discrepancies are caused by the transport of higher salinity water from West Cote Blanche Bay into the vicinity of Site 1. This indicates that the movement of the freshwater river plume, as well as the circulation of the western bays, is not correctly predicted with the NOGAPS wind forcing. It should be pointed out though that the monthly salinity values of the LAR, WLO, and Jaws Bay outlet may be too high for early January, leading to an overprediction of the minimum salinity values at Site 1 following the third cold front. As discussed in WH00 there is also a significant rainfall event on January 7 that is not captured by the model. This rainfall event could presumably create salinities at Sites 1 and 3 that are lower than the monthly mean salinity values used for the rivers in our simulation. The model salinity at Site 1 captures the correct trends in the observations after January 9 but with a bias of about 1–2 psu.

It should also be emphasized that Site 1 is near a salinity front created by the intrusion of the river plume water into the western bays. This makes an accurate prediction of the exact salinity at Site 1 quite difficult due to its sensitivity to the location of the front. The front itself is quite sensitive to the wind, tide, and river discharge at any particular time. This sensitivity is apparent from the fluctuations in the measured salinity values in Figure 8A. The surge in river discharge following the rainfall event on January 7 (WH00) is another discrepancy between the model and the actual scenario that could create differences between the measured and predicted salinities at Sites 1 and 3.

Salinity is underpredicted during the southerly wind of January 1–5. The model salinities decrease rapidly between January 1 and January 3 because the southeasterly model winds are steady whereas the observed winds were weaker, more variable, and more easterly. This causes a decrease in salinity at Site 1 because the Atchafalaya river plume water is transported westward into West Cote Blanche Bay. The river plume's offshore westward transport intensifies around January 5 and water levels decrease in the West Cote Blanche Bay. Higher salinity water, which has been confined to the inner western bays, is transported southeastward into the vicinity of Site 1. This leads to the rapid increase in the salinity at Site 1 after January 5. The discrepancy between the model and the observations at Site 1 is thus consistent with the error in the modeled water levels at Luke's Landing. This process is examined in more detail in a companion paper (Cobb, Keen, and Walker, 2008).

The salinity of the model at Site 3 (Figure 8B) is in better agreement with the observations than at Site 1. The peaks associated with the cold fronts are in phase and have the same duration as the observations. The model also reproduces the salinity fluctuations seen in the measurements quite well, especially between December 31 and January 4. It should be pointed out that these large salinity fluctuations are generated by the inflow of higher salinity offshore water through Southwest Pass (WH00). The model and the observations disagree between December 28 and 31 because of the larger measured incoming and outgoing currents (Figure 7B), which create greater fluctuations in the measured salinity at Site 3. Following this event, the predicted salinity trend matches the observations quite well; however, the model has a bias of approximately 2 psu between January 5 and 11. This bias is most likely the result of the Vermilion River, Cypremort Point GIWW Outlet, and Jaws Bay discharge salinities being too high prior to the validation period (see Table 4) and perhaps the rainfall event on January 7 as well. It should also be pointed out that the model-data agreement for the current velocity at Site 3 improves after December 31 as well (Figure 7B) in conjunction with the improvement in salinity. The processes that determine the salinity fluctuations at Site 3 are discussed further in Cobb, Keen, and Walker (2008).

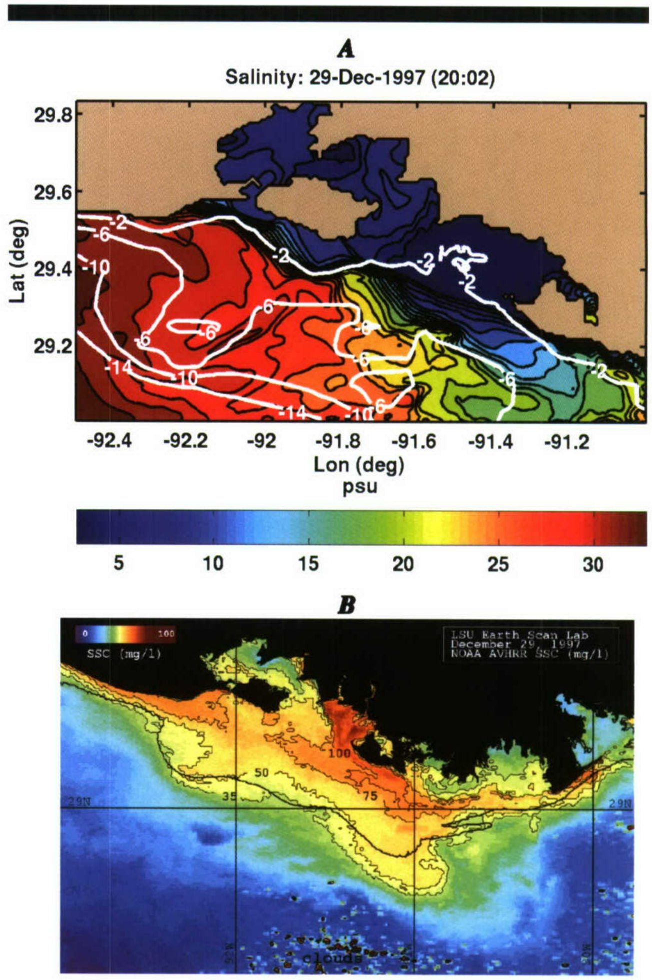

Figure 9. (A) Surface salinity contours (1.5-psu interval) for December 29, 1997 (20:02), predicted by the numerical model. The isobaths between 2 and 14 m are plotted at 4-m intervals in white. (B) NOAA-14 AVHRR derived satellite imagery of suspended sediment concentration (mg/L) for December 29, 1997 (20:38) UT. SSC were estimated using the algorithm presented in Myint and Walker (2002). The black contour line indicates the 10-m isobath.

The Atchafalaya Surface Plume

The preceding comparisons between the model and the observations have been at isolated points. However, it is also important to evaluate the shelf-scale dynamics of the river plume being simulated by NCOM. The southeastern edge of the predicted plume can be conveniently delineated by the 20 psu isopleth on December 29, 1997 (Figure 9A); the isobaths from 2 to 14 m have been plotted at 4-m intervals in white over the salinity contours in Figure 9A. This snapshot represents the plume during the postfrontal northwesterly winds of the second cold front. It is also apparent from Figure 9A that the plume water discharged from Atchafalaya Bay is moving parallel to the bathymetric contours and is being channeled between essentially the 2- and 6-m isobaths. The core of the plume can be seen in Atchafalaya Bay where the salinity is less than 5 psu. Other areas of freshwater exist in the western bays and along the coast in the vicinity of Marsh Island.

The higher salinity water southwest of Atchafalaya Bay (~20–30 psu) is the result of the river plume water mixing with high salinity (>30 psu) water when it is forced offshore by strong postfrontal northerly winds around December 27. This well-mixed edge of the river plume appears to be bounded to a great extent by the 10-m isobath as it is displaced to the southeast. In addition, the salinity contours in the western section of the domain reflect the shoaling of the bathymetry in this region (as seen from the bathymetry contours in Figure 9A). These postfrontal salinity patterns are qualitatively similar to field measurements reported by KINEKE *et al.* (2006). In particular their observations display a correlation between salinity and bathymetry that is similar to the behavior predicted by the model. This is further evidence of how strongly the bathymetry influences the circulation as well as the mixing of plume water in the shelf region. These offshore mixing processes will be addressed further in COBB, KEEN, and WALKER (2008).

Clear-sky NOAA AVHRR imagery is used to examine surface sediment concentrations (SSC) in the Atchafalaya Bay region during the northwesterly wind episode of the second frontal passage on December 29, 1997 (Figure 9B); the black contour line indicates the 10-m isobath. The estimated surface sediment concentrations are the result of strong postfrontal northwesterly winds (average wind speed around 9 m/s) that pushed the Atchafalaya plume in a southeastward direction. The isopleths of SSC are proxies for salinity because the dominantly cohesive sediment in the plume flocculates and settles as salinity increases; thus, higher salinity produces lower SSC values. The SSC isopleths of Figure 9B appear to be well correlated with the salinity patterns predicted by the model in Figure 9A. In particular the 35–50 mg/L SSC isopleths are correlated with the higher salinity water (20–30 psu) southwest of Atchafalaya Bay, and the 75 mg/L isopleth is well correlated with the plume water southeast of Atchafalaya Bay at (91.3° W, 29.2° N). In addition the 100 mg/L isopleth correlates quite well with the low salinity plume water within Atchafalaya Bay. It should also be pointed out that the SSC appears to reflect the bathymetric contours of Figure 9A as does the salinity. These correlations indicate that the offshore Atchafalaya river plume dynamics are being captured by the numerical model during the passage of the cold fronts.

DISCUSSION

The main objective of this work is to validate a robust and realistic numerical simulation of the hydrodynamics of the Atchafalaya Bay region. This objective has been achieved, based on comparisons of the model-predicted water levels, current velocities, and salinity at various locations to *in situ* observations made by WH00. In addition the offshore river plume motion has been validated by comparing NOAA AVHRR satellite estimates of surface suspended sediment concentrations (MYINT and WALKER, 2002; WALKER and HAMMACK, 1999; WH00) to the surface salinity predicted by the model at approximately the same time on December 29, 1997. Despite the overall good agreement between the model and the observations, however, several discrepancies have been identified. It is important to understand the source of these errors so that they can be corrected in subsequent simulations. Thus, we discuss the errors and what can be done to correct them in future modeling studies of the Atchafalaya Bay region.

Accurate atmospheric forcing is critical to coastal circulation modeling in all but tide-dominated regions. This study has used the NOGAPS operational model because it is readily available and has been thoroughly examined as a global atmospheric prediction system (*e.g.,* HOGAN and BRODY, 1993). However, NOGAPS has a horizontal resolution of 1° (approximately 100 km), which is very coarse compared with the 5-km and 800-m grids used in this study. The underprediction of the postfrontal wind is probably due to this resolution, which precludes strong pressure gradients and thus strong wind vectors from developing. This problem has been addressed by the development of mesoscale models like COAMPS (Coupled Ocean-Atmosphere Mesoscale Prediction System) (HODUR, 1997), which use spatial resolutions of less than 5 km.

The ABG domain was also forced with the measured winds from Cypremort Point to determine if more accurate wind forcing would improve the model results. This involved applying the time varying, but spatially invariant, wind vectors measured at Cypremort Point over the entire ABG domain. Unfortunately the spatially invariant wind forcing generated numerical instabilities during the periods of strong winds regardless of whether the winds were obtained from the Cypremort Point data or NOGAPS. This strongly suggests that spatially variable wind forcing is necessary for achieving realistic simulations of the complex baroclinic circulation that occurs in the ABG domain.

Bathymetric effects dominate circulation in shallow water, especially in enclosed bays and estuaries. Thus it is necessary to examine the model's response to barotropic flows, which are sensitive to bathymetry. The tidal water levels predicted by NCOM show overall good agreement with historical tides but errors occur at a site (Rabbit Island Pass) in relatively shallow water (1.83 m at the RB location). This indicates a probable error in the older bathymetry used for this area of the bay. It is well known that oyster reefs existed seaward of Rabbit Island Pass and at the mouth of Atchafalaya Bay until they were dredged completely in the 1970s (STONE, ZHANG, and SHEREMET, 2005). These reef structures are most certainly reflected in the older ABG bathymetry used for this study and thus affect the tides predicted by the model at RB as well as within the bay system. Of course, the IHO database is not of recent origin and may reflect some of the same uncertainties introduced in generating the ABG model grid. The solution to this problem is to use better (*i.e.,* more recent) bathymetry, but the incompleteness as well as the age (the surveys were performed in 1934) of the 90-m NOAA bathymetry used for this study demonstrates how difficult this can be.

The water level observations from Luke's Landing (Figure 6) show that the inner bays are flushed out by the strong postfrontal northerly winds and inundated by the steady southerly winds that occur between cold fronts. The model predictions also show that this occurs, but there is a discrepancy between the model and the measured water levels between January 5 and 8; the measured water level keeps rising after January 5 whereas the model water level starts decreasing. An inspection of the overall circulation reveals that on January 5 the river plume's westward flow, driven by the overpredicted southerly winds of NOGAPS, strengthens significantly. We infer from this that the weaker southerly and easterly winds measured at Cypremort Point do not reestablish the westward flow of the river plume as quickly as the NOGAPS winds. Thus the measured water level continues to rise at Luke's Landing and the measured salinity continues to decrease at Site 1 for a longer period than is predicted by the simulation.

The model-observation comparisons of the current velocity at Sites 1 and 3 indicate that the model is reproducing the correct trends in the circulation if not the correct magnitudes. A comparison of the model current velocities with the tide-only current velocities of the model at Sites 1 and 3 (not plotted) shows that the current is dominated by the tides except during very strong wind events (*i.e.,* postfrontal winds). The IHO tidal validation supports the wind–tide forced currents of the model because the dominant motion at these locations is tidal. Therefore, we expect the flood tide amplitudes and phase of the model currents at Sites 1 and 3 to be in good agreement with the observations and the ebb tide currents to be underpredicted by the model. The agreement during strong wind events depends on the accuracy of the NOGAPS winds because wind forcing is more important than tidal forcing during these events.

The salinity results demonstrate that the model is reproducing the overall circulation patterns within the region. Sites 1 and 3 are particularly sensitive to the hydrodynamics because they are exposed to moving salinity fronts; thus they provide a useful metric through which the overall circulation, as well as the river plume motion, can be evaluated. If the simulated river plume diverges too much from the actual river plume motion, there should be significant phase differences between the NCOM salinity and the observations at Site 1. It therefore appears reasonable that the error in the model salinity at Sites 1 and 3 can be accounted for by differences between the magnitude and direction of the NOGAPS and the measured winds. An example of this is the NOGAPS winds between the second and third cold fronts, which are stronger and more southerly than the measured winds. The model-observation comparisons at LL and Site 1 both suggest that the model's river plume dynamics diverge from the actual river plume dynamics during this period. In addition a significant rainfall event not captured by the model may also be lowering the salinity and increasing the river discharge after January 7 (WH00). This rainfall event might account for some of the differences between the model and the measured salinity during the passage of the third cold front.

The preceding discussion demonstrates that the circulation within the bay system is affected by changes that occur in the bathymetry over long periods. The overall robustness of the simulated hydrodynamics suggests, however, that the circulation and general behavior of the river plume do not change significantly unless there are major changes in the morphology of the bays and/or their respective freshwater sources. Thus, for example, if the sediment load of the Atchafalaya River were increased significantly as part of a future coastal conservation project, the bay system's bathymetry could be substantially altered, resulting in significant changes to their nearshore circulation as well. This would also be true for dredging projects, which might dump spoils in sensitive areas. We can speculate that our present understanding of the hydrodynamics of the Atchafalaya Bay system are sufficient to put fish recruitment and shellfish harvesting studies on a more solid foundation, giving biologists a comprehensive and predictive approach for determining changes in the baroclinic circulation of a region. Having the capability to simulate the three-dimensional baroclinic hydrodynamics of the bay systems could potentially allow coastal engineers to predict the impact of pollution, dredging, and large scale coastal projects on the regional ecosystems, preventing substantial losses to the fishing industry and the environment as a whole.

CONCLUSION

This study describes a three-dimensional numerical model (Navy Coastal Ocean Model) of tide, river, and wind-forced circulation in the Atchafalaya Bay region, which is part of the Mississippi River outflow in the northern Gulf of Mexico. The Atchafalaya Bay model is nested to a northern Gulf of Mexico model, which is itself nested to the global NCOM. This approach permits realistic effects from nonlocal processes like tides and synoptic atmospheric forcing such as cold fronts. The model system described in this work can be used to better understand river-dominated circulation in this region and applied to the long-term management of Louisiana's coastal ecosystem as well as the future development of its natural resources.

The models are validated by comparison with measurements taken within the bays and the adjacent inner shelf during the passage of cold fronts in December 1997 and January 1998. The innermost nested model, which includes both large and small sources of freshwater, accurately reproduces the baroclinic and barotropic flows within the bay as evidenced by the observations. Discrepancies between the model predictions and the measured hydrographic data are caused, to a large extent, by uncertainties in the model's wind forcing and freshwater sources (*i.e.,* river discharge, local rainfall runoff, and salinity values). The older bathymetry used for the inner bays and inner shelf also appears to be a significant source of error in the model results.

This work lays the foundation for further studies of circulation in the Atchafalaya Bay system and for future studies of fine-grained sediment transport. The interactions of the tide, river, and wind-forced circulation during cold fronts are examined in a companion paper (COBB, KEEN, and WALKER, 2008). Although the current paper and its companion paper only focus on a brief period, they do capture in detail the dominant circulation processes at work in the Atchafalaya Bay system during the winter months. As illustrated further in part 2 of this study, the interactions of the river plume with the inner bays and adjacent shelf are essential to understanding sediment transport in the region and the details of these (relatively brief) interactions must be thoroughly investigated.

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